Center of Excellence for the Synthesis and Processing of Advanced Materials: Review – June 12, 2003

"Defect Structures and Properties in Rare-Earth-Ba-Cu-O Cuprate Superconductors"

David O. Welch

Brookhaven National Laboratory

Project Coordinator

A Project of the Center of Excellence for the Synthesis and Processing of Advanced Materials:

"Defect Structures and Properties in Rare-Earth- Ba-Cu-O Cuprate Superconductors"

Participating Institutions:

Ames Laboratory, Argonne National Laboratory,
Brookhaven National Laboratory, Oak Ridge Laboratory,
Los Alamos National Laboratory, and Sandia National Laboratory

Project Coordinator:

David O. Welch, BNL

CSP Review: "Defect Structures… in Cuprate Superconductors"

This project involves groups funded by BES and/or the "Superconductivity for Electric Systems" program, Office of Energy Efficiency and Renewable Energy.

New Feature:

Collaboration with AFOSR Coated Conductor MURI

- “The key to better engineering lies in the knowledge of imperfections in materials”

  quoted from an advertisement of a professorship in the Materials Science and Technology Department, Faculty of Applied Sciences,

  TU Delft, Physics Today, February 2001

- “Like people, materials are interesting because of their faults.”

  Sir Charles Frank

Active Collaborative Projects

- Basic Properties of RE-123 Compounds
  - Substitution Effects on Superconductivity
  - Systematics of Thermophysical Properties

  Ames: McCallum, Kramer   ANL: Veal
  BNL: Welch, Su (Caltech)

- Defect Structures and Critical Currents in YBCO Coated Conductors

  ANL: Miller, Veal   ORNL: Goyal, Christen, Feenstra, Lee
  BNL: Suenaga, Welch   LANL: Holesinger, Foltyn
  SNL: Clem, Siegal

"Collaborations" (cont.)

- **Grain boundaries, in YBCO**

ANL:	Veal, Paulikas, Berghuis, Claus, Gray
BNL:	Suenaga, Welch, Su, Zhu
ORNL:	Christen, Goyal
LANL:	Holesinger

- **Flux Pinning**

BNL:	Suenaga, Welch
ORNL:	Christen, Feenstra
LANL:	Foltyn, Holesinger

Activities

- “Caucuses” at Fall MRS (November 2002);
  EERE “Superconductivity for Electric Systems” Program Wire Development Workshop (January 2003);
  EE Superconductivity Peer Review (July 2003).

- Workshop on “Zoology and Ecology” of Defects and Nanoscale Structure in 123-Phase Superconductors, BNL, October 2003

- Review article on state-of-the-art

Some Research Highlights

- Coated Conductors
- Grain Boundaries
- Flux Pinning

Coated Conductors

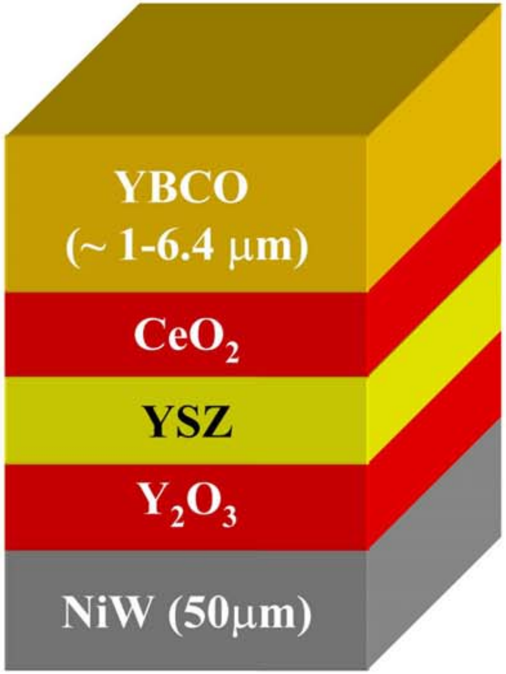
- Coated Conductor Architecture: Buffer Layers and Defects

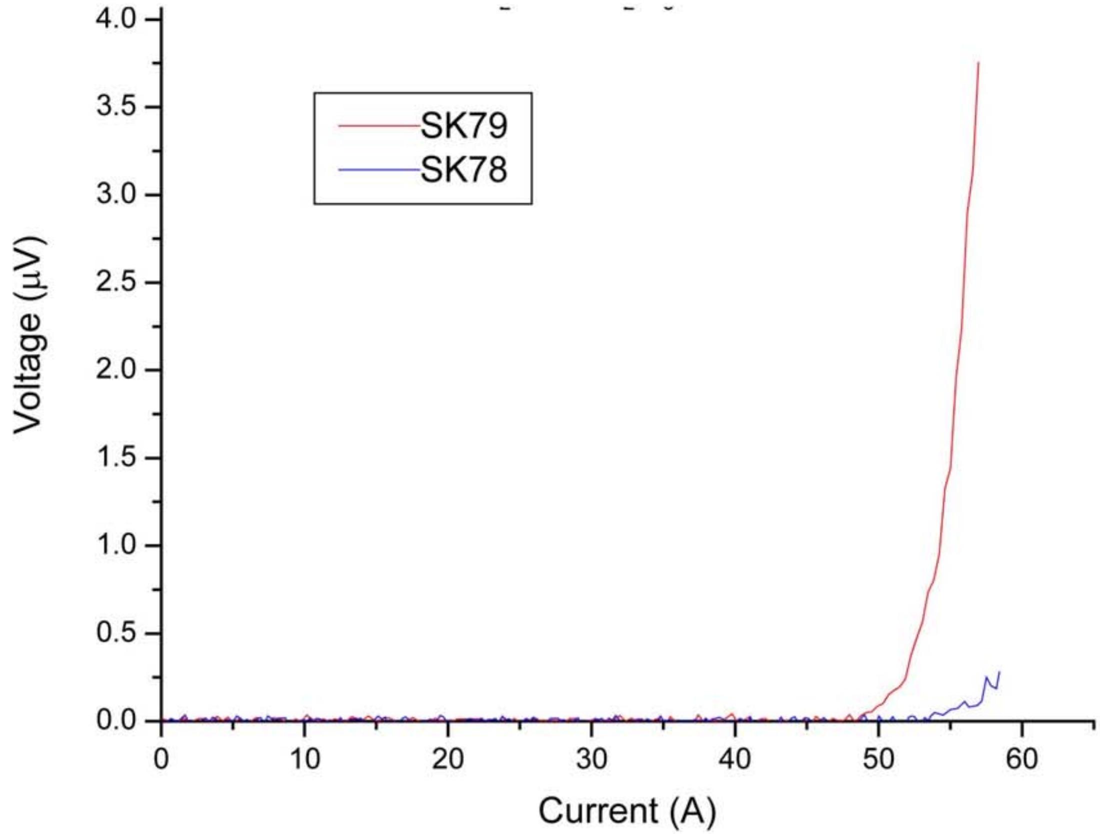
  ORNL, LANL, SNL, BNL

- The BaF_2 process for ex-situ YBCO growth

  ANL, BNL, ORNL, SNL, LANL
  - Growth and Characterization
  - Thickness Dependence of J_c

PLD YBCO films on buffered Ni-W substrates





Sample No. SK78, 5 mm wide

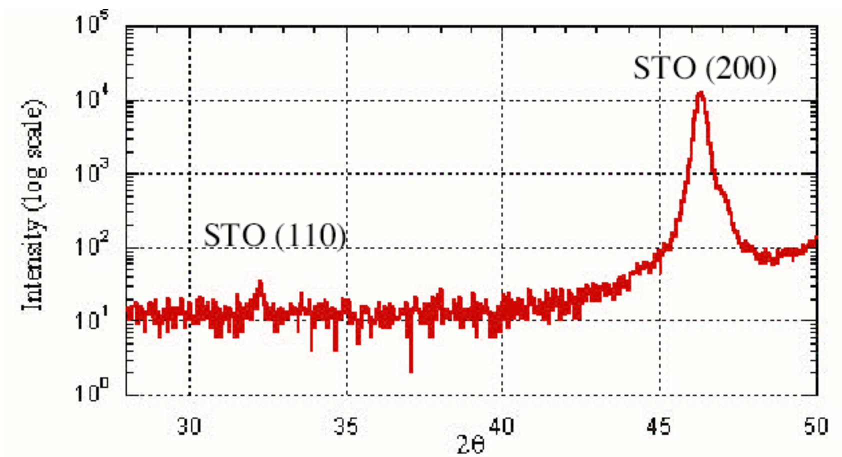
YBCO Thickness: 1.00 μm

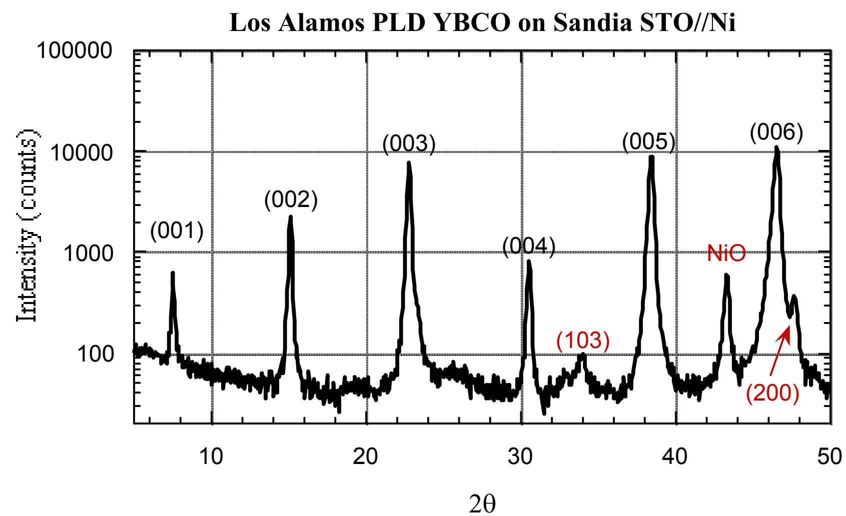
I_c = 59A (self-field, 77K), I_c/width = 118 A/cm; J_c = 1.18 MA/cm^2

Stress-Induced Nanocracks in YBCO Coated-Conductors Due to Oxygen Diffusion Through STO Buffer Layers

M. Siegal, P. Clem and J. Dawley **(Sandia)**
S. Folytn and T. Holesinger **(Los Alamos)**

Goal: grow thick YBCO films on sol-gel buffered metal tapes





Highly-oriented STO grows easily on $Ba_{0.2}Ca_{0.8}TiO_3$//Ni(100) templates.

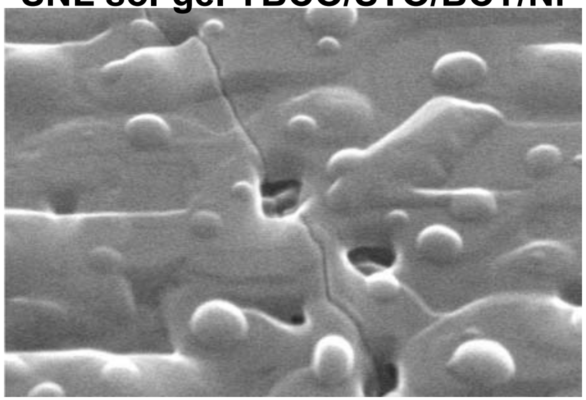
1.3 µm thick YBCO by PLD (LANL) on STO/BCT/Ni by sol-gel (SNL)
note presence of NiO!

Great c-axis orientation, T_c = 87 K, however J_c(75K) < 1000 A/cm². WHY? → Nanocracking

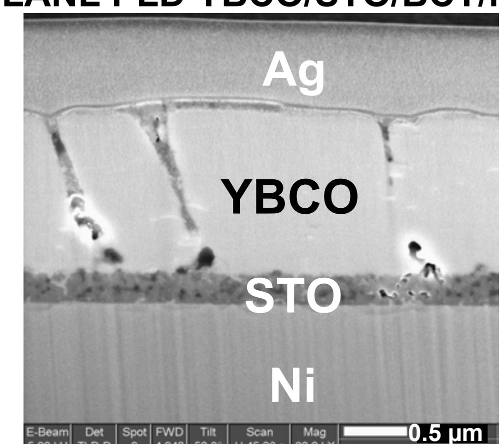
Nanocracking, Oxygen Diffusion, Stress….

Nanocracking
(from PLD or sol-gel)
greatly limits supercurrent!

SNL sol-gel YBCO/STO/BCT/Ni

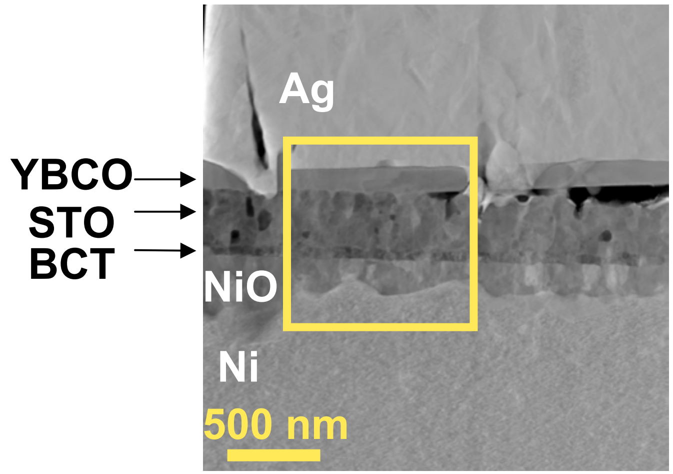


LANL PLD YBCO/STO/BCT/Ni



What causes nanocracking?

Dark-field STEM image

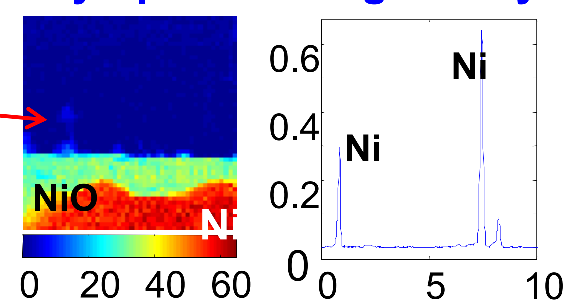


Significant NiO at buffer/Ni interface.

Resulting YBCO layer has nanocracks.

X-Ray Spectral Image Analysis

note the protrusion of NiO into the STO buffer region above the substrate

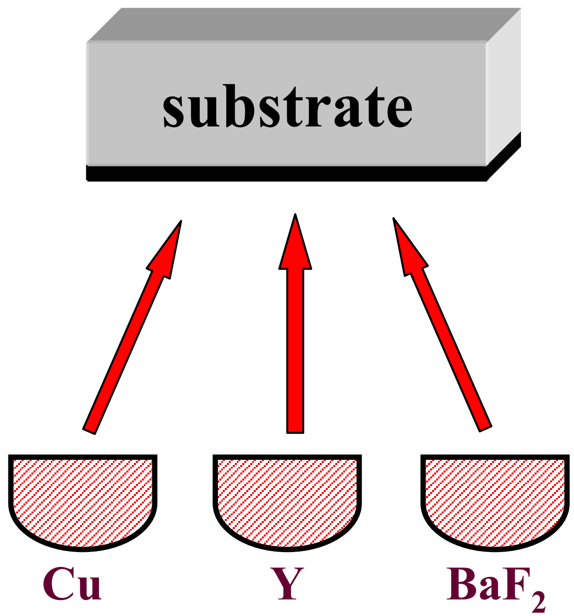


Different thermal expansion coefficients → ***STRESS***

YBCO Thick Film Synthesis

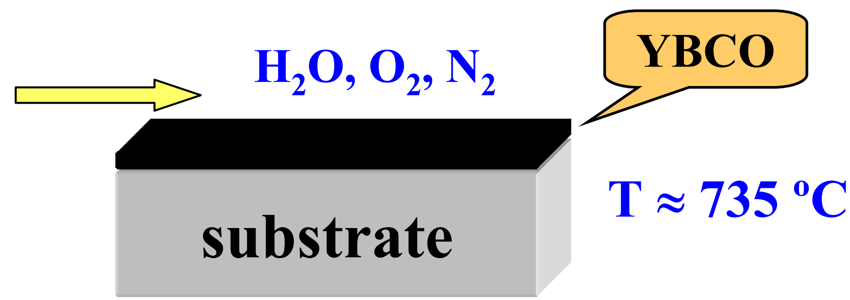
YBCO Precursor Deposition

E-beam evaporation



V.F. Solovyov, H.J. Wiesman
DMCS, BNL

Textured YBCO Formation by a post-deposition reaction process



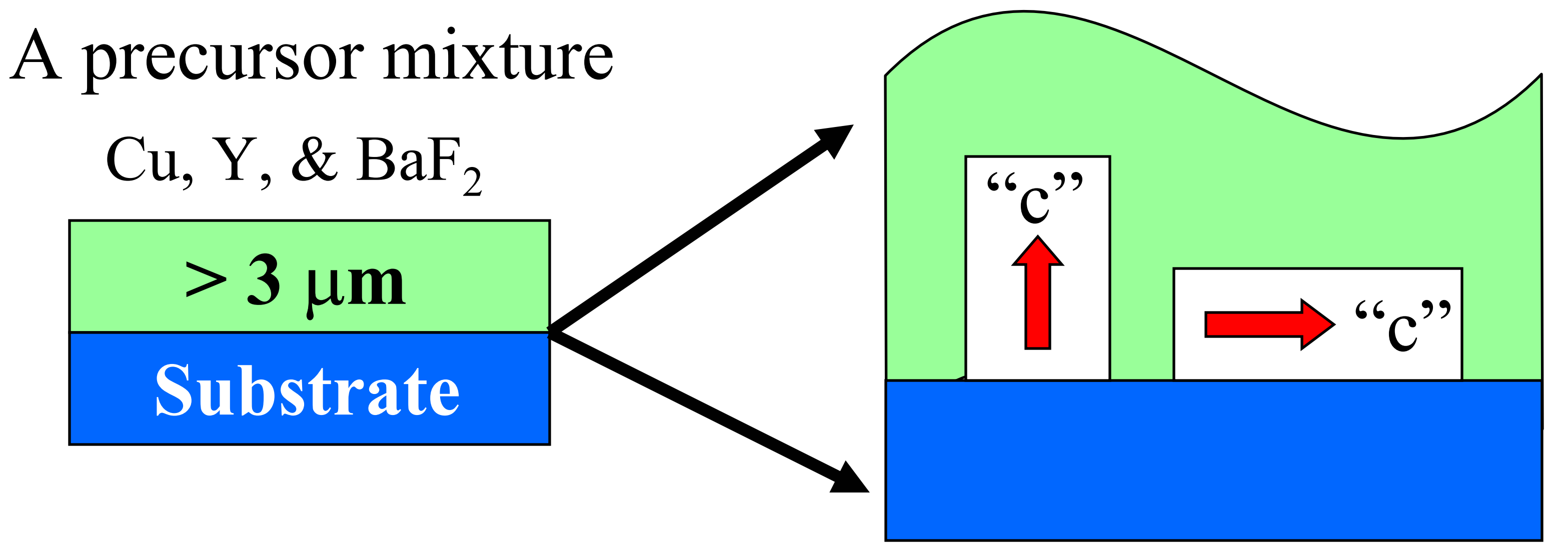
$Cu + Y + BaF_2 + H_2O + O_2$

$\Rightarrow Cu_2O +$ (Y,Ba) $(O,F)_2$ $+ H_2O + O_2$

$\Rightarrow YBa_2Cu_3O_{\sim 6.1} + HF$

Nucleation of Epitaxial YBCO

❍ How does an oxide epitaxially nucleate and grow from a buried interface at the substrate surface ?



Department of Energy
Brookhaven Science Associates

Thickness dependence of J_c in YBCO coated conductors

Ron Feenstra, A. A. Gapud, D. K. Christen, E. D. Specht, A. Goyal,
Oak Ridge National Laboratory

D. M. Feldmann, D. C. Larbalestier, *University of Wisconsin*

T. G. Holesinger, P. N. Arendt, *Los Alamos National Laboratory*

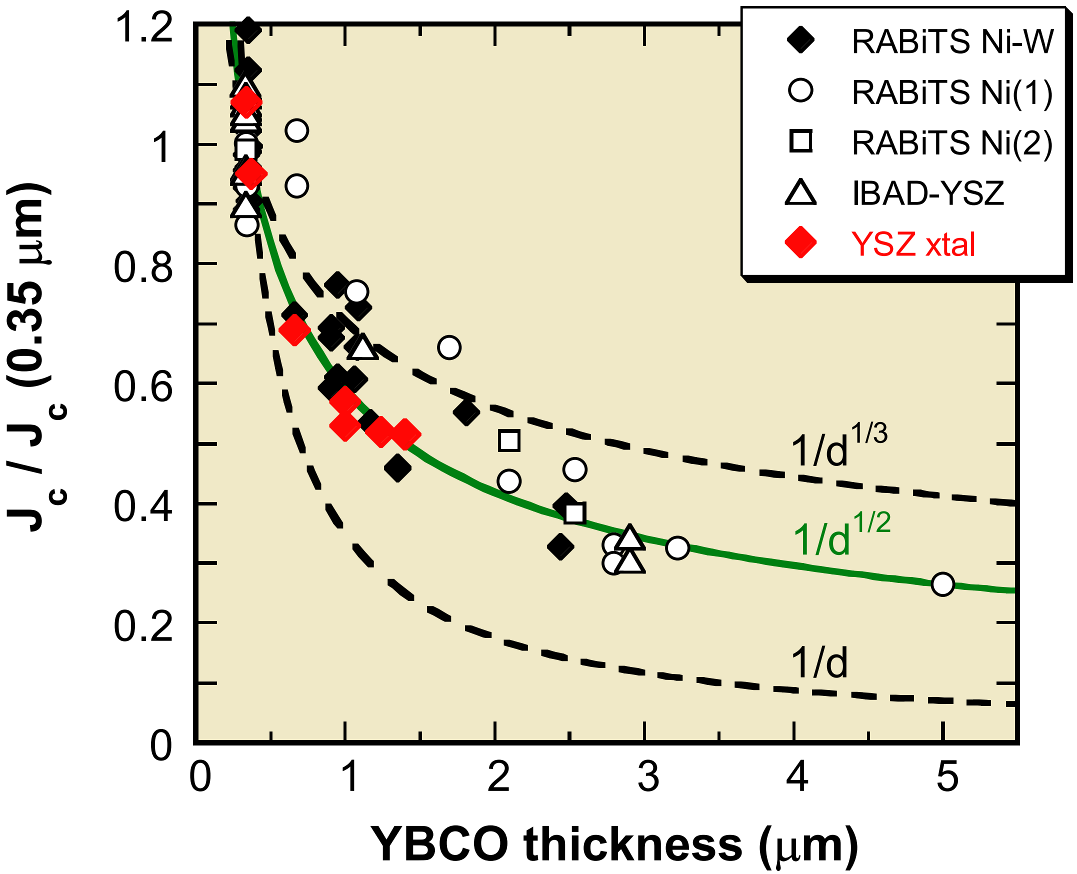
Los Alamos

UT-BATTELLE

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Collaborative research is performed to determine intrinsic and materials effects on $J_c(d)$

- YBCO films grown at ORNL (BaF_2 ex situ process)
- through-thickness J_c (stepwise thinning) measured at UW
- microstructure analyzed at LANL

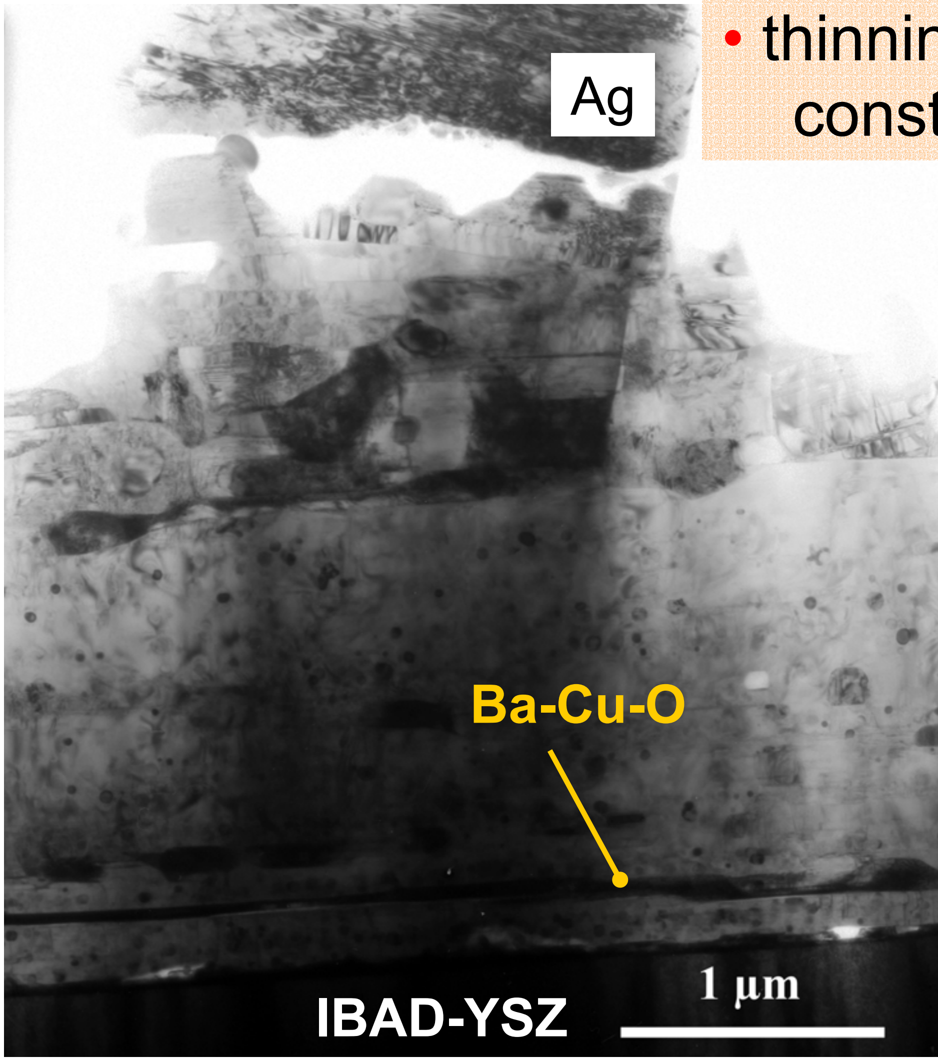


- $J_c(d)$ (on normalized scale) is independent of substrate: RABiTS, IBAD-YSZ, crystal
- $J_c(d) \propto 1/d^{1/2}$
  - qualitatively consistent with 2D collective pinning model
- similar $J_c(d)$ observed for PLD

UT-BATTELLE
Oak Ridge National Laboratory
U. S. Department of Energy

TEM reveals bi-layer-like structure in thick YBCO

- suggestive of different growth modes
- thinning study (Univ. Wisconsin) → constant J_c through thickness



YBCO (small-grains)

YBCO (large-grains)

CeO_2

YBCO (2.9 μm) / IBAD-YSZ
I_c = 240 A/cm (77 K)

Los Alamos

UT-BATTELLE

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Reel-to-reel characterization of YBCO coated conductors: Formation of YBCO from "BaF_2" precursor

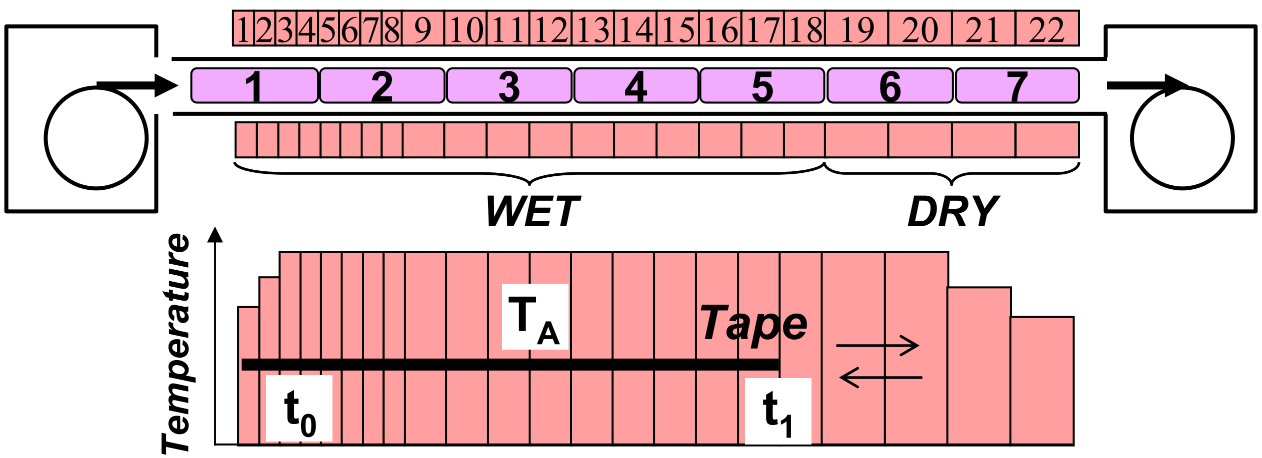
PI's: ANL – V. Maroni ORNL – D. F. Lee

Objectives: To study ex-situ YBCO formation using complementary R-R XRD and Raman techniques.

To investigate the possibility of using these techniques for in-situ monitoring.

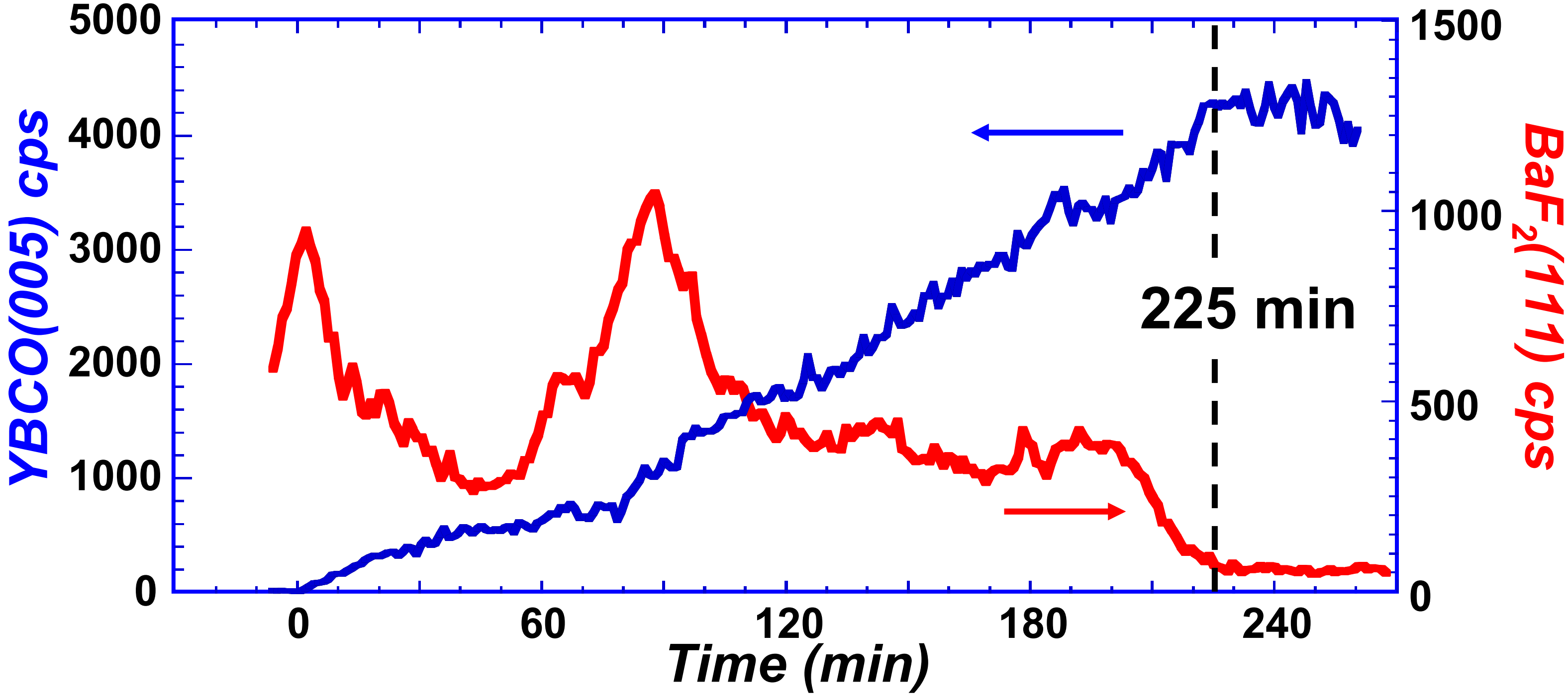
Sample Preparation

- RABiTS tape with "BaF_2" precursor is pulled into furnace with a set profile.
- Once the front of the tape has reached time t_1, the sample is re-wound onto cold payout reel at 2m/min.
- Sample consists of ramp-up section and section in which anneal time at T_A varies from zero to t_1 - t_0



Reel-to-Reel XRD has been shown to be invaluable In aiding the optimization of processing conditions

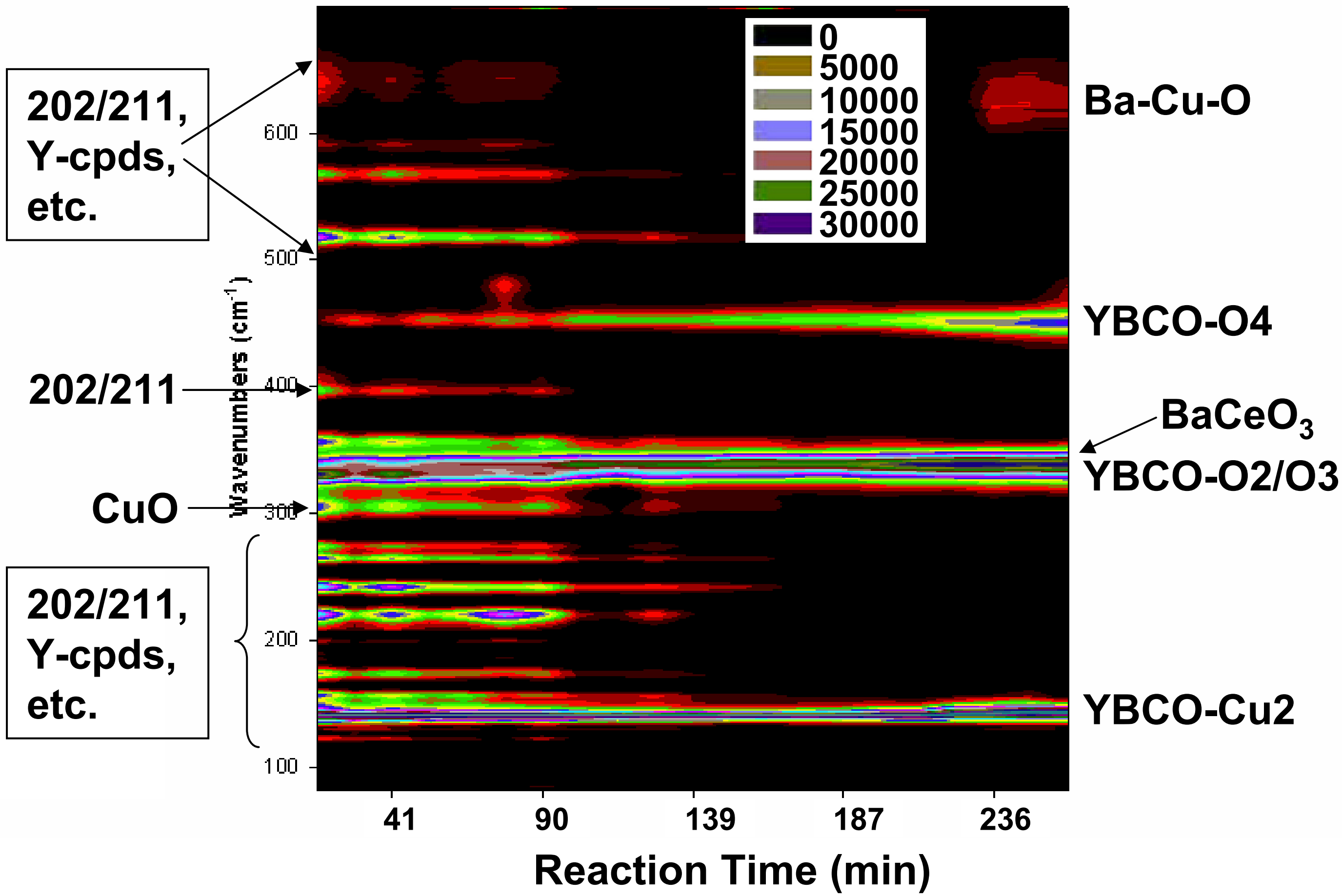
- Predominance of c-axis YBCO growth as well as extent of reaction can be monitored.
- 1 μm-thick YBCO shows disappearance of BaF_2(111) and leveling of YBCO(005) at roughly 225 min.
- YBCO (00l) intensity has been found to be closely associated with J_c.



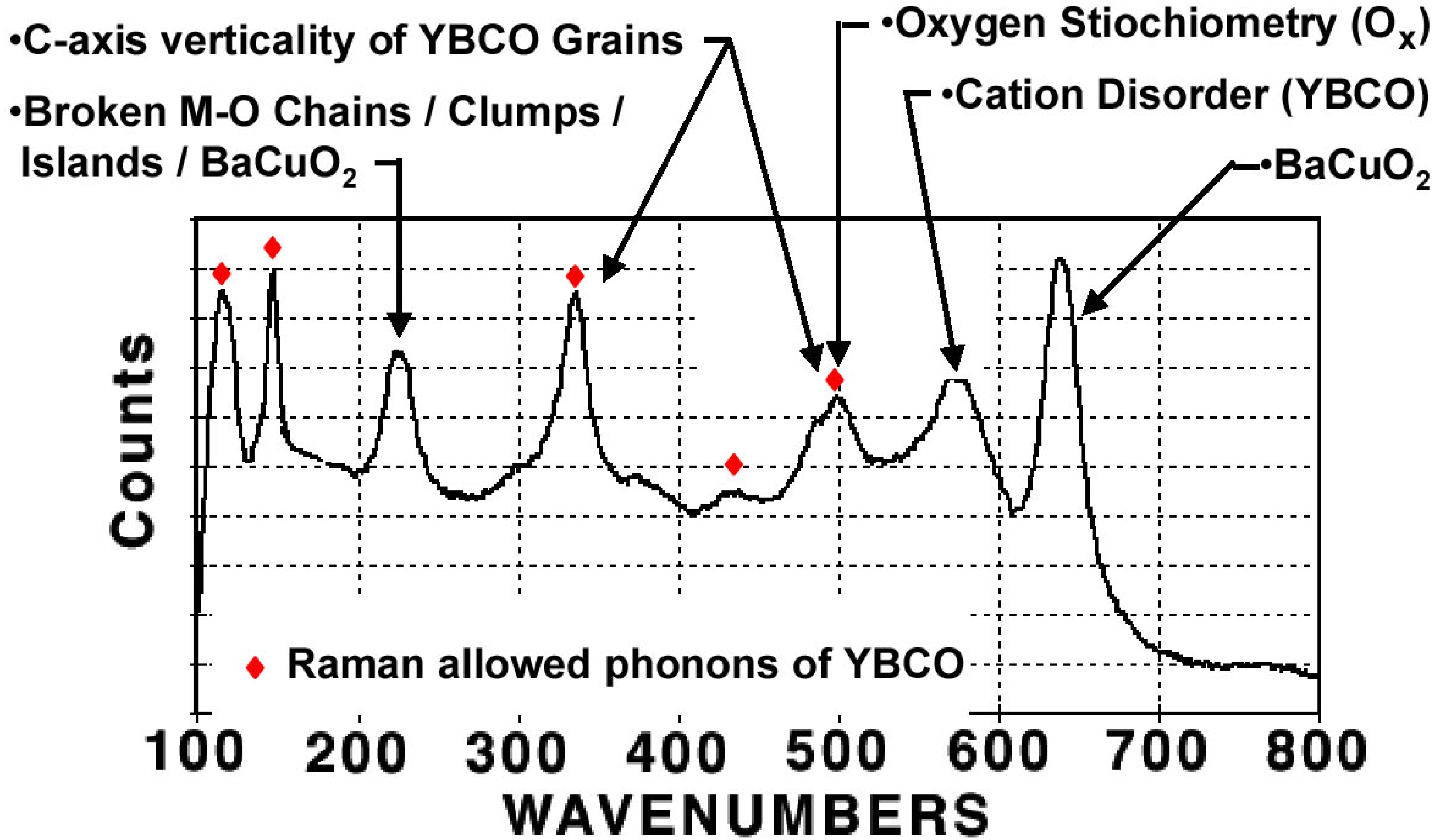
- <u>However</u>, it is difficult to distinguish and track the presence of other phases that participate in the YBCO formation process.

Reel-to-Reel Raman is a complementary technique that can provide information not available from XRD

- **R-R Raman shows both the phases participating in the reaction (LHS) as well as the products (RHS) as a function of annealing time.**
- **Raman scans on the same 1 μm-thick tape show that YBCO formation is completed (appearance of Ba-Cu-O) at roughly 230 min.**



Raman Spectroscopy Reveals Many Details about Composition and Microstructure of YBCO Films



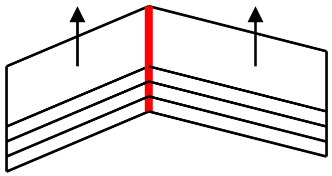
Grain Boundaries

- Space Charges, Stress, Doping, Oxygenation

  ANL, BNL, ORNL, LANL

Improved interfacial superconductivity via Ca doping

$Y_{1-x}Ca_xBa_2Cu_3O_7$

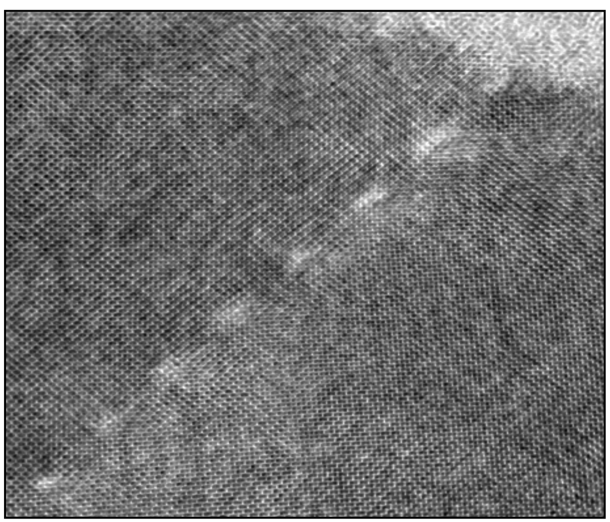


4° [001] Tilt Boundary
Samples from
C. Joos, Göttingen Univ.

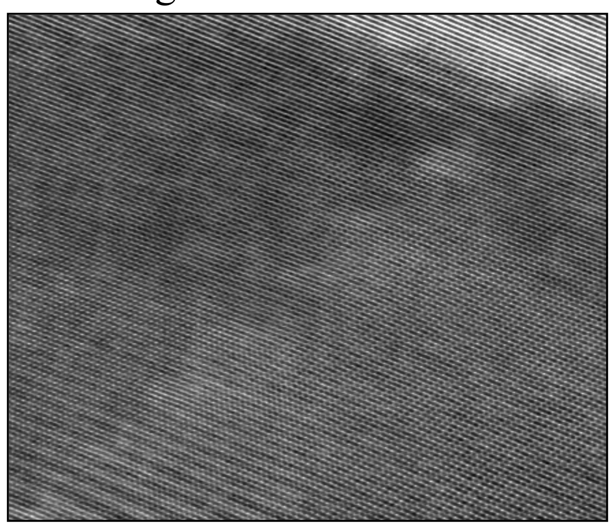
film-GB angle	J_{gb}^{GB} [10^6 Acm^{-2}]	J_c [10^6 Acm^{-2}]	J_{gb}^{GB}/J_c
undoped 8° [001]	7-11	30-38	0.26
doped 8° [001]	11-21	30-35	0.49
undoped 4° [001]	10-15	25-33	0.43
doped 4° [001]	6-9	10-16	0.58

Critical current densities at 4.2 K for doped and undoped films calculated from *magneto-optical* measurements (B_{exp} ≈100 mT).

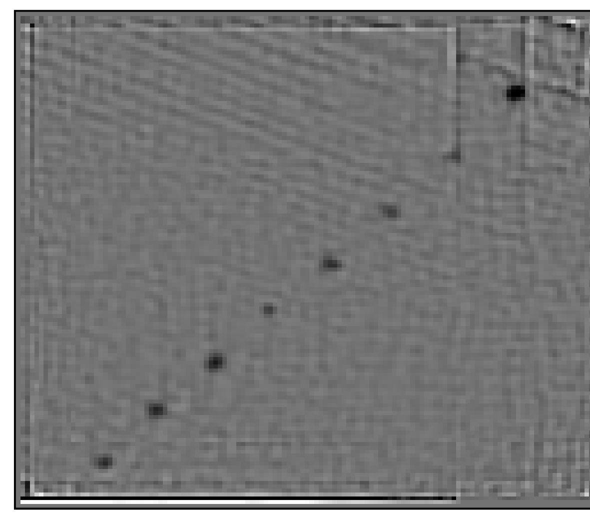
HREM



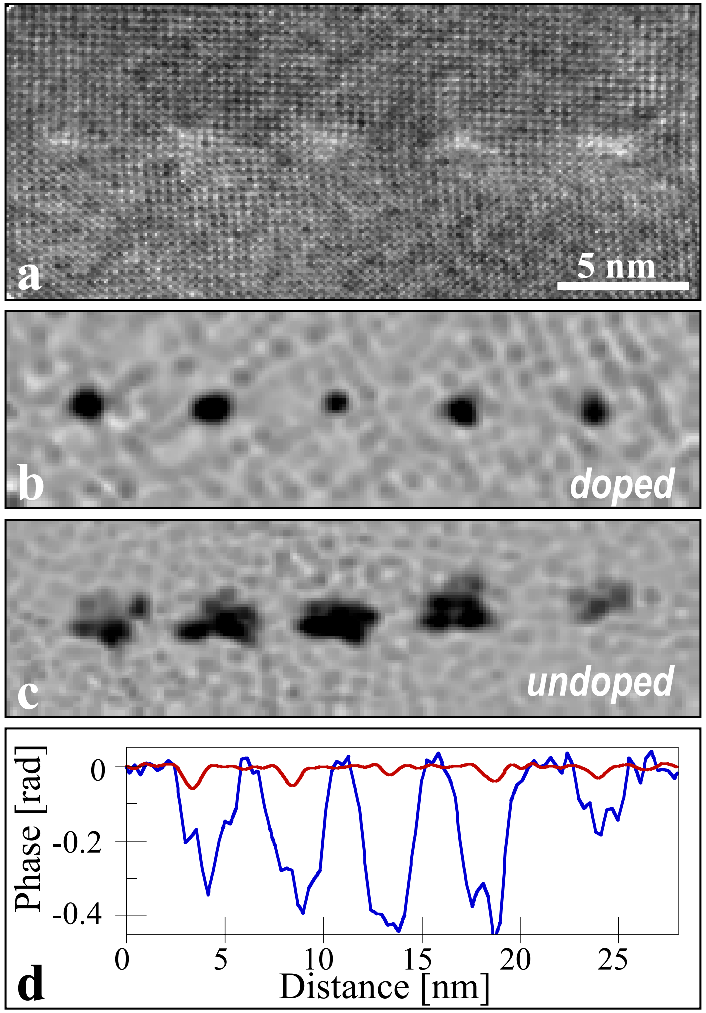
hologram



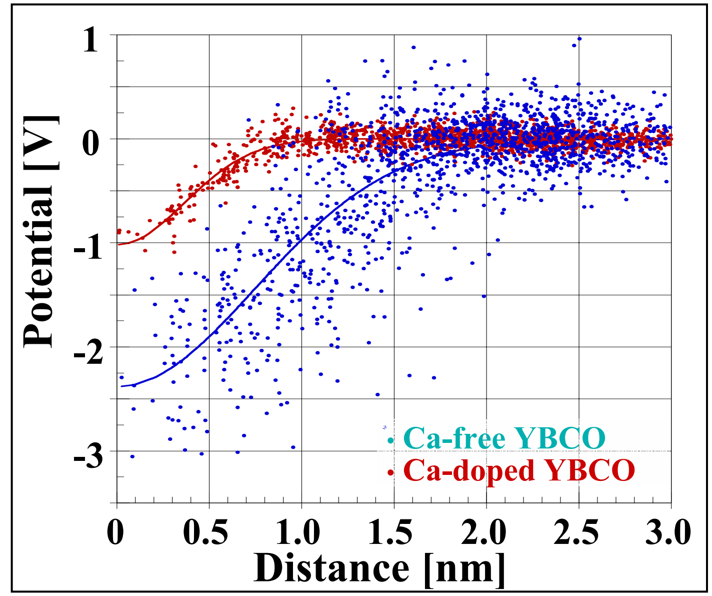
phase



Electrostatic potential variation : YBCO GB w/o Ca doping



Phase shift from holography



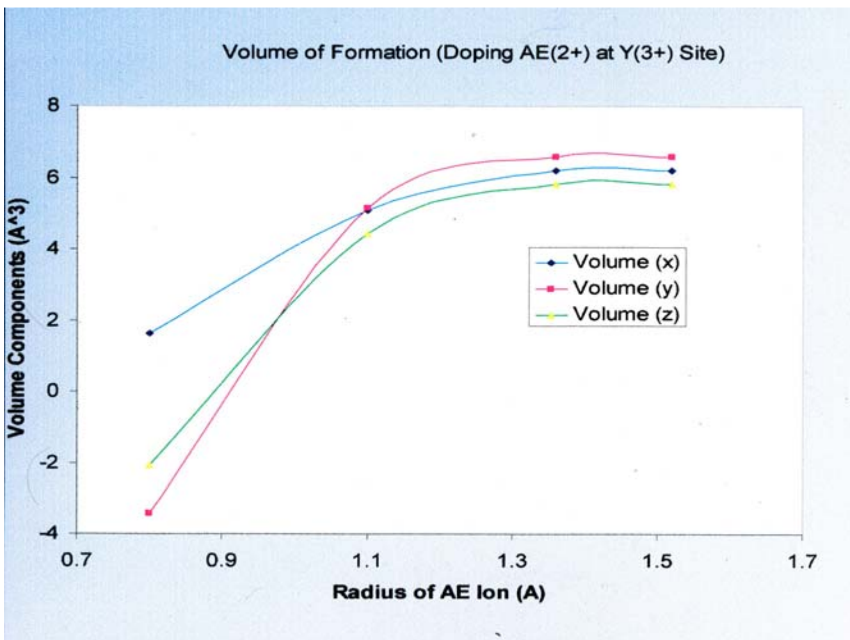
Projected potential around the GB core

Theoretical Studies

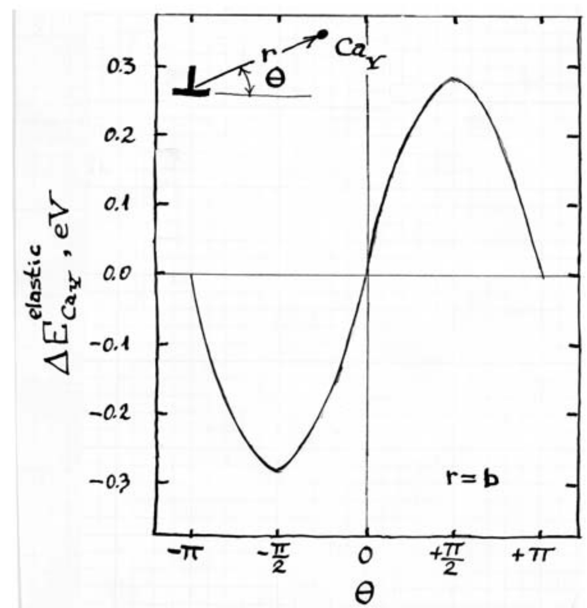
Stress-Field Interaction with Defects: $E_{defect}(\sigma) \cong \boldsymbol{E_o} - \sum_{i,j} \sigma_{ij} \boldsymbol{V_{ij}}$

(E_o, V_{ij} computed by atomistic simulation.)

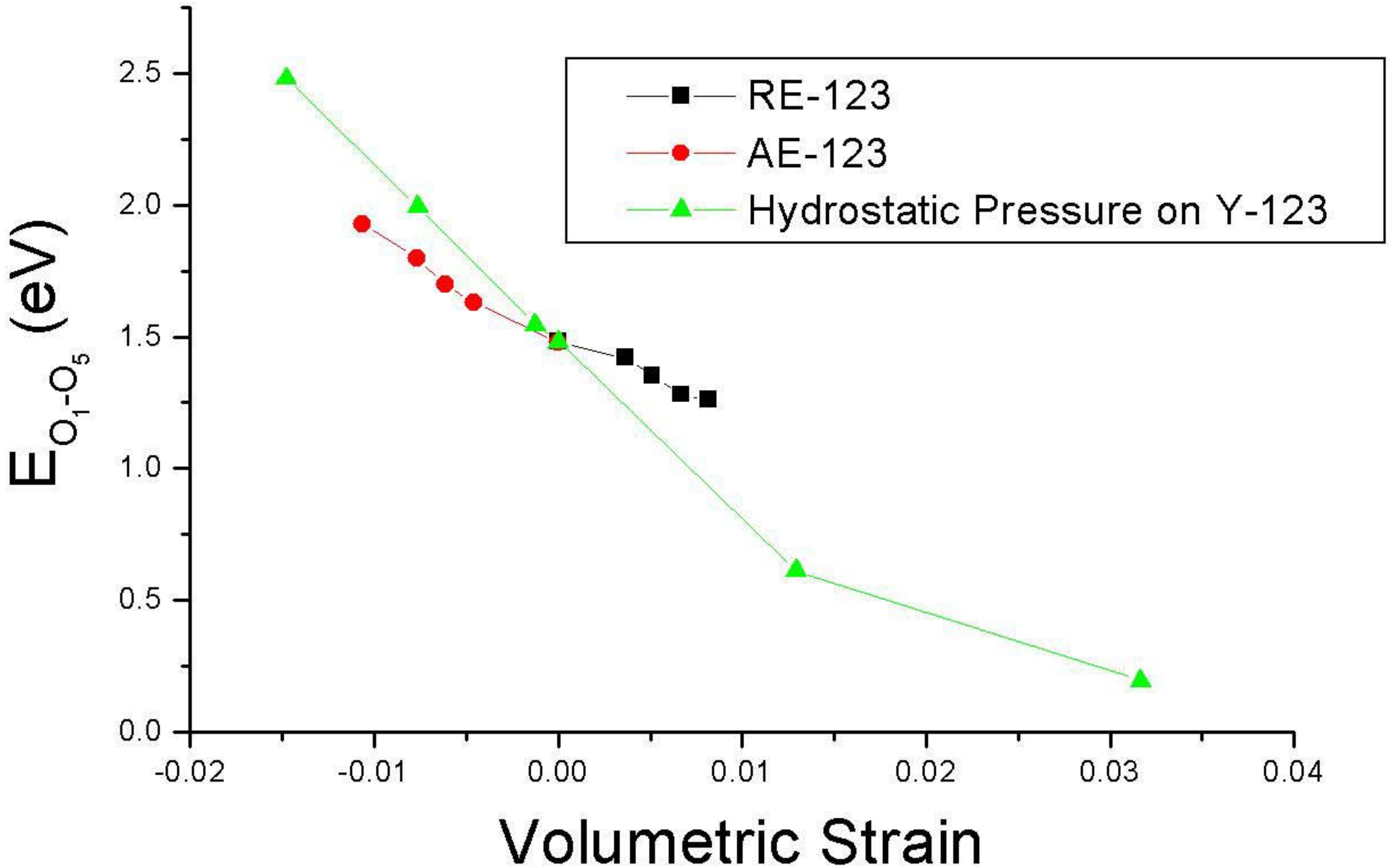
Volume of Formation (Doping AE(2+) at Y(3+) Site)



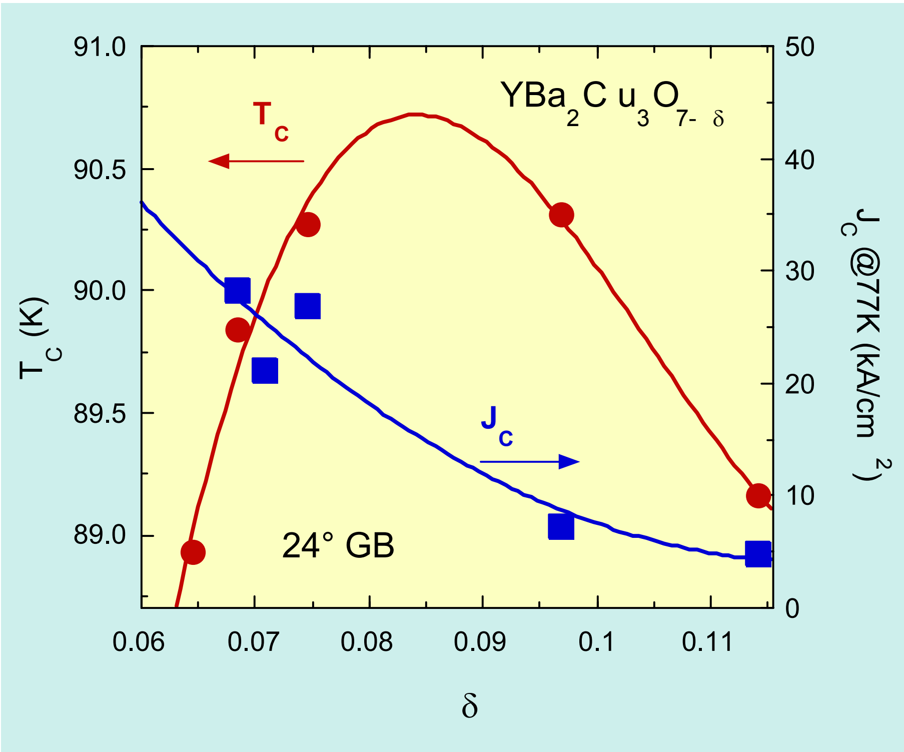
Ca elastic interaction with a dislocation

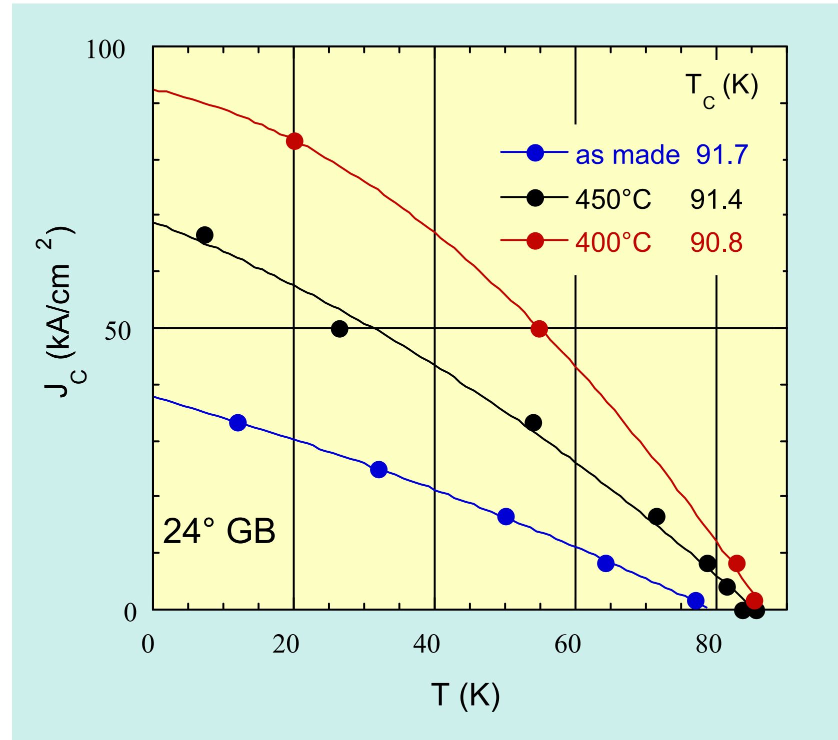


Frenkel Pair Formation Energy for 123 Phase



Oxygenation of grain boundaries



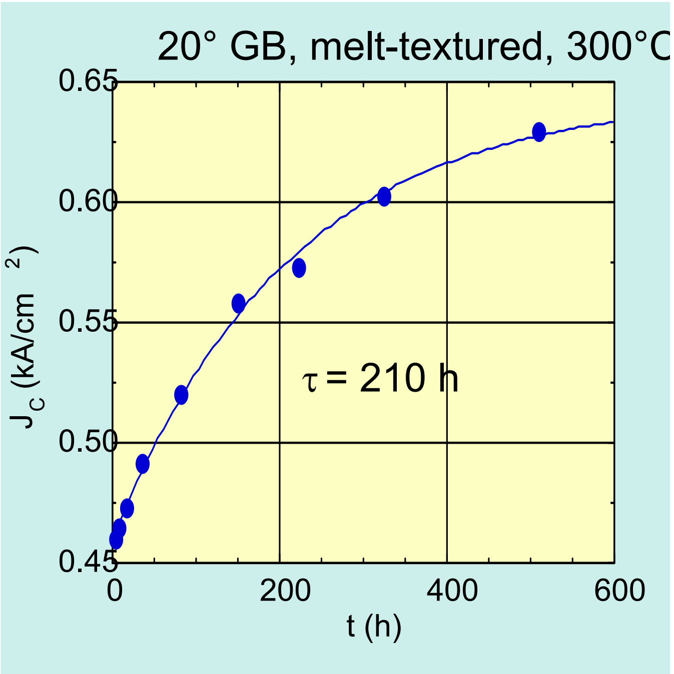


As the oxygen concentration is increased, the film T_C goes through a maximum at optimum doping. However, J_C continues to increase in the overdoped regime. Results were obtained from a 24° grain boundary.

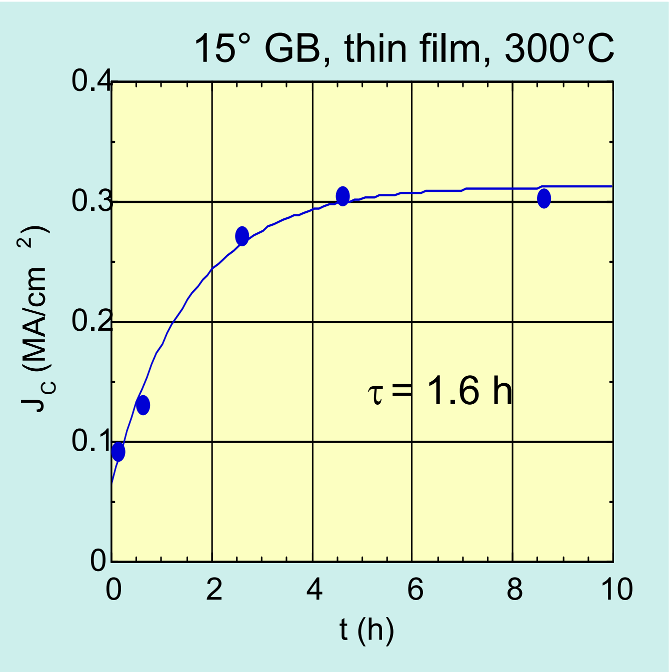
Improvement in J_C is observed at all temperatures when the level of oxidation is increased. Listed are oxygenation temperatures and T_C values. Reducing the annealing temperature (e.g., to 400 C in O_2) increases the oxygen stoichiometry. A smaller enhancement in J_C is observed as the GB angle becomes smaller.

Oxygenation of thin film GBs is much faster than bulk GBs

Bulk grain boundary



Thin film grain boundary



Samples were initially equilibrated at 450° in flowing O_2. They were then oxygenated at 300°C for the indicated times. $J_C(t) = J_{C0} + \Delta J_C (1-\exp(-t/\tau))$

• Oxygenation of thin-film GBs is ~ 100 times faster than bulk GBs

Flux Pinning

- What pins the flux?
  ANL, BNL, LANL
- Improving flux pinning
  Ames, LANL
- ac losses in thin films
  Ames, BNL, LANL

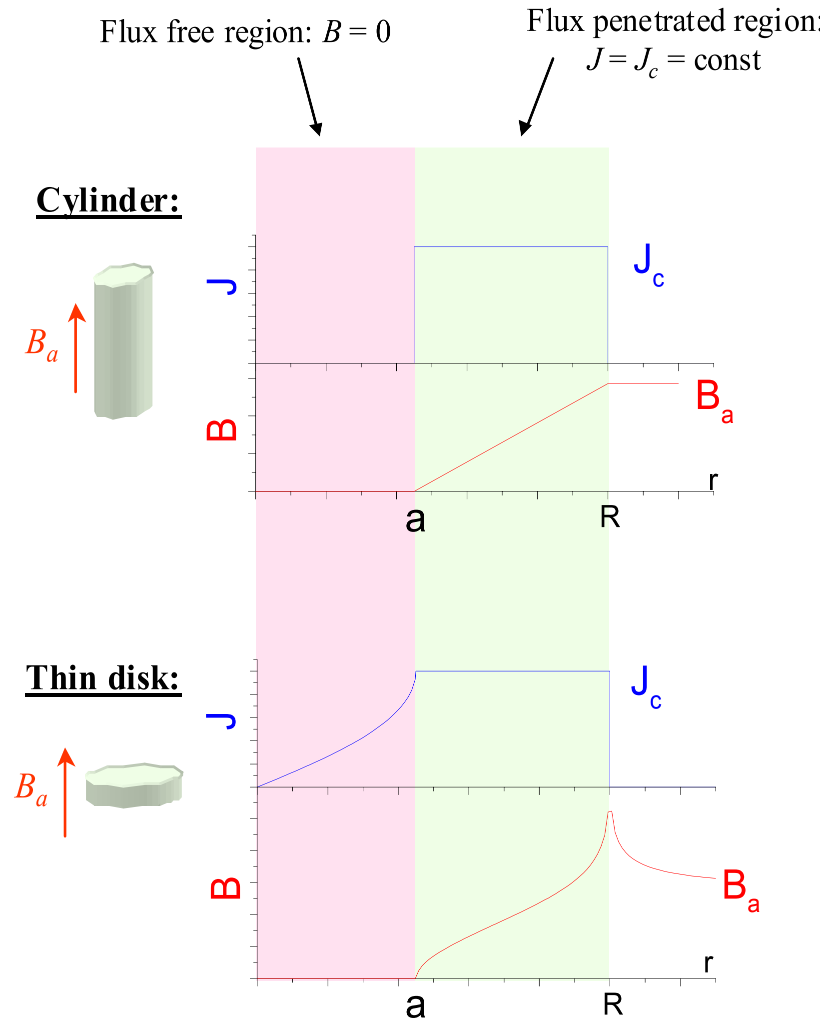
ac losses in circular disks of YBCO films in perpendicular magnetic fields

M. Suenaga/BNL

S. R. Foltyn/LANL

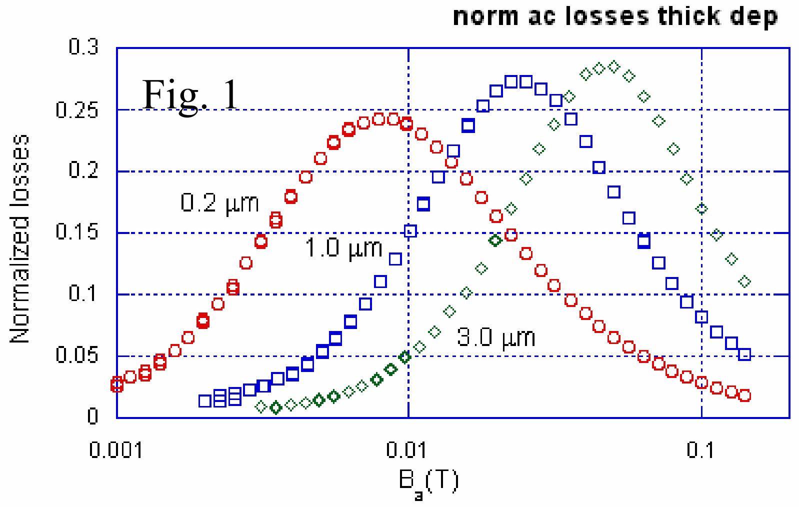
The figure illustrates the difference in the magnetic field penetration into a long cylinder and a thin disk. This difference results in significant differences in the properties of superconductors in magnetic fields such as ac losses.

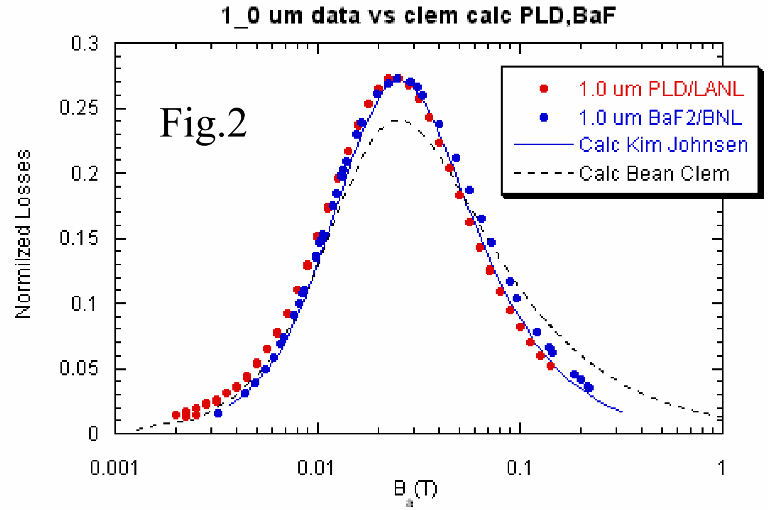
The Bean model



BROOKHAVEN NATIONAL LABORATORY

ac losses in thin circular disks of YBCO in perp. magn. fields





Normalized losses = $[Q(B_a)/(8R/3\pi d)]/(\pi B_a^2/\mu_0)$

Fig. 1. Thickness dependence of the losses

Fig. 2. Comparisons of theoretical predictions based on the use of the field independent and dependent critical current densities for 1 µm thick films.

YBCO films on $SrTiO_3$ by (1) pulsed laser deposition by S. R. Foltyn/LANL and (2) BaF_2 process by V. F. Solovyov/BNL, and measured by M. Suenaga/BNL

Conclusions:

1) The low field losses are determined by $1/(J_c\ d)^2$ rather than $1/J_c$ for bulk where d is the thickness of the film.

2) The use of the field dependent $J_c(B)$ is necessary for calculating the losses for moderate to high magnetic fields.

BROOKHAVEN NATIONAL LABORATORY

New Activities in the Final Year Before "Graduation"

- Quantitative description of nanoscale structure
- A workshop to consolidate what we know and what we don't about the "zoology and ecology" of defects and nanostructure in RE-123 [at BNL, October 2003]
- A review article to summarize where we stand on defects and nanostructures in RE-123